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ORIGINAL ARTICLE

Changes in the pollen seasons of the early flowering trees *Alnus* spp. and *Corylus* spp. in Worcester, United Kingdom, 1996–2005

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Abstract Previous work on *Betula* spp. (birch) in the UK and at five sites in Europe has shown that pollen seasons for this taxon have tended to become earlier by about 5–10 days per decade in most regions investigated over the last 30 years. This pattern has been linked to the trend to warmer winters and springs in recent years. However, little work has been done to investigate the changes in the pollen seasons for the early flowering trees. Several of these, such as *Alnus* spp. and *Corylus* spp., have allergens, which cross-react with those of *Betula* spp., and so have a priming effect on allergic people. This paper investigates pollen seasons for *Alnus* spp. and *Corylus* spp. for the years 1996–2005 at Worcester, in the West Midlands, United Kingdom. Pollen data for daily average counts were collected using a Burkard volumetric trap sited on the exposed roof of a three-storey building. The climate is western maritime. Meteorological data for daily temperatures (maximum and minimum) and rainfall were obtained from the local monitoring sites. The local area up to approximately 10 km surrounding the site is mostly level terrain with some undulating hills and valleys. The local vegetation is mixed farmland and deciduous woodland. The pollen seasons for the two taxa investigated are typically late December or early January to late March. Various ways of defining the start and end of the pollen seasons were considered for these taxa, but the most useful was the 1% method whereby the season is deemed to have started when 1% of the total catch is achieved and to have ended when 99% is reached. The cumulative catches (in grains/m^3) for *Alnus* spp. varied from 698 (2001) to 3,467 (2004). For *Corylus* spp., they varied from 65 (2001) to 4,933 (2004). The start dates for *Alnus* spp. showed 39 days difference in the 10 years (earliest 2000 day 21, latest 1996 day 60). The end dates differed by 26 days and the length of season differed by 15 days. The last 4 years in the set had notably higher cumulative counts than the first 2, but there was no trend towards earlier starts. For *Corylus* spp. start days also differed by 39 days (earliest 1999 day 5, latest 1996 day 44). The end date differed by 35 days and length of season by 26 days. Cumulative counts and lengths of season showed a distinct pattern of alternative high (long) and low (short) years. There is some evidence of a synchronous pattern for *Alnus* spp.. These patterns show some significant correlations with temperature and rainfall through the autumn, winter and early spring, and some relationships with growth degree 4s and chill units, but the series is too short to discern trends. The analysis has provided insight to the variation in the seasons for these early flowering trees and will form a basis for future work on building predictive models for these taxa.

Keywords Pollen seasons · Temperature · Chill hours · Growth degree days · Climate change

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Introduction

In northern and central Europe and northern America, pollen from trees in the order Fagales, which includes the genera *Alnus* spp. and *Corylus* spp., represent important allergen sources both in their own right and due to cross-

reactivity with *Betula* spp., another member of the order (Matthiesen et al. 1991; D'Amato and Spieksma 1992). *Alnus* spp. and *Corylus* spp. pollen acts as a primer making allergic people more sensitive to other pollens later in the season. Earlier seasons for the early spring species may cause stronger reactions during the birch pollen season by giving a longer period of priming in susceptible individuals so that their allergic reactions occur at a lower birch threshold concentration (Emberlin et al. 1997).

In the British Isles, the genus *Corylus* spp. is represented by *Corylus avellana*. *Alnus glutinosa* is the native representative of the genus *Alnus*, and is often found alongside riverbeds, although *A. cordata* and *A. incana* are popular ornamental species (Preston et al. 2002). In Britain, the pollen seasons of *Alnus* spp. and *Corylus* spp. typically last from early January to late March or early April, although there is annual variation between start dates, duration and severity. Previous work (Frenguelli et al. 1993) has demonstrated that a significant correlation exists between the beginning of pollination and the temperature during the period preceding the pollen season. For *Corylus* spp., strong correlations have been found between the mean temperature for the last 10 days in December and the start of the pollen season, largely because *Corylus* spp. requires only a very short period of heat accumulation after vernalisation.

Global average surface temperatures increased by 0.6± 0.2°C over the twentieth century, and a further increase of 1.4 to 5.8°C is projected by 2100. In Europe, warmer temperatures produced the warmest decade (1990–1999) on instrumental record, annually and for winter (IPCC 2001; Ahas et al. 2002). Such increases in temperature have caused the length of the growing season to increase, on average, by about 10 days since the early 1960s (Menzel and Fabian 1999; IPCC 2001). It has been shown that plants flowering early in spring are more affected by warming than species flowering later in the year (Ahas et al. 2002; Fitter and Fitter 2002). This relationship is non-linear and does depend on the amount of vernalisation received (Emberlin et al. 2002).

This paper aims to investigate changes and features in the pollen seasons of the early flowering spring species of trees, *Alnus* spp. (alder) and *Corylus* spp. (hazel) in Worcester from 1996–2005, in this context.

Materials and methods

Pollen monitoring

Daily average concentrations of *Alnus* spp. and *Corylus* spp. pollen were monitored at the National Pollen Network site at Worcester, for the years 1996–2005. Worcester is situated in the West Midlands, UK; 184 km northwest of London and 52 km south of Birmingham.

Airborne pollen was collected using a Burkard volumetric trap (Hirst 1952) situated on the exposed roof of a three-storey building at the University of Worcester (52°11′N, 2°14′W) at a height of 10 m above ground. The pollen monitoring site is approximately 1.4 km from the city centre of Worcester. The pollen was collected by standard British Aerobiology Federation methods and the pollen concentration was expressed in terms of the number of pollen grains per unit volume of air (British Aerobiology Federation 1995). The local vegetation is mixed farmland and deciduous woodland and the local area up to approximately 10 km surrounding the site is mostly level terrain with some undulating hills and valleys.

Climate and meteorological data

The climate in Worcester is western margin maritime temperate and is characterised by an annual mean temperature of (1961–1990 average) 3°C in January and 16°C in July (Meteorological Office 2004). The mean annual total rainfall in the West Midlands is approximately 600 mm (1971–2000 average) (Meteorological Office 2004). The weather is influenced by the passage of anticyclones and fronts moving in from the Atlantic, and as a result has a tendency to fluctuate rapidly (Goudie 1996).

The Meteorological Office via the British Atmospheric Data Centre supplied the meteorological (temperature and rainfall) data used in this study. The data were taken from the two Meteorological Office surface stations situated closest to Worcester, approximately 15 km to the southeast of the pollen-monitoring site: Pershore College of Horticulture (52°6′N, 2°03′W) from 1975 to 2002, and Pershore (52°8′N, 2°02′W) from 2002 to 2005. The two stations are about 4.9 km apart. These Meteorological Office stations hold the most complete and accessible datasets for the period studied.

Mean monthly temperature and mean monthly cumulative rainfall data from October 1975 to April 2005 were used as a base to which weather conditions during, and in the months preceding, the *Alnus* spp. and *Corylus* spp. pollen seasons examined in this study could be compared. Thirty years were used because it is a period defined by the World Meteorological Organization as long enough to eliminate year-to-year variations (Meteorological Office 2004; Muñoz-Díaz and Rodrigo 2004). Temperatures during the study period were also compared to mean monthly Central England Temperatures (CET). The CET began in 1659 and is the longest available instrumental record of temperature in the world (Meteorological Office 2005).

Analysis of pollen seasons

A number of methods were considered for defining the start and end dates of the *Alnus* spp. and *Corylus* spp. pollen seasons. A threshold method, such as defining the start of the pollen season as the day when the cumulative daily count reached a certain figure (Σ75 or Σ100 method) (Dreissen et al. 1989, 1990; Adams-Groom et al. 2002) or by defining the beginning and end of the season as the first and last days when the daily pollen count is greater than or equal to a certain threshold (Sanchez-Mesa et al. 2003), was not used in this study because in some years very little pollen was recorded in the season and so mandatory thresholds may not have been reached. Instead, retrospective methods that define the season as the period in which 90% (Nilsson and Persson 1981), 95% (Goldberg et al. 1988) and 98% (Emberlin et al. 1993) of the total season's catch occurred were investigated.

Relationships between meteorological parameters (temperature and precipitation data) and characteristics of the *Corylus* spp. and *Alnus* spp. pollen seasons were investigated using correlation and regression analysis. Start dates were entered into the analyses with mean monthly and 10-day mean temperature and rainfall data from October (the previous year) to February (in the year of pollination).

Chilling and heat requirement

Chilling hours were calculated following the method of Aron (1983), which is based on the accumulation of chilling hours between 0 and 7.2°C (Aron 1983; Frenguelli and Bricchi 1998; Jato et al. 2000; Rodríguez-Rajo et al. 2004):

$$CH = 801 + 0.2523\ B + 7.57\ B^2 \times 10^{-4} - 6.51\ B^4 \times 10^{-10} - 11.44\ T_{\min} - 3.32\ T_{\max}$$

CH = *number of Chilling Hours during period*

$$B = 24\ D\ (Threshold - T_{min})/(T_{max} - T_{\min})$$

where T_{min} and T_{max} are the average minimum and maximum temperatures recording during the period respectively, and D is the length of the study period in days.

Chilling was deemed to have commenced when mean daily temperatures were ≤12.5°C for two or more consecutive days. The threshold of 12.5°C was chosen because this is the temperature below which winter flowering woody plants are considered to begin to satisfy their chilling requirements (Richardson et al. 1974; Faust 1989; Jato et al. 2000). It was not possible to define the end of chilling as the first day when the mean daily temperature reached the minimum values and started to follow a positive trend (Rodríguez-Rajo et al. 2003) or by taking the end of chilling to be when the mean daily temperatures were >7.2°C (Galán et al. 2005), which are methods used successfully by other authors, because on average (October 1975 to April 2005 mean) these thresholds were passed after the *Corylus* spp. and *Alnus* spp. pollen seasons had already started. The end of the chilling period was therefore defined using an arbitrary date that was determined after examining the results of correlation analysis between start dates of the *Corylus* spp. and *Alnus* spp. pollen seasons and temperature data from the preceding months.

The heat requirements of *Alnus* spp. and *Corylus* spp. were obtained from the sum of the daily mean temperatures after deducting different base temperatures (4, 4.5, 5, 5.5 and 6°C) and expressed as growth degree days (GDD°C) (Frenguelli and Bricchi 1998; Jato et al. 2000). Other methods for calculating heat requirement were considered, but because of the need for brevity it was not possible to mention every method employed in the study. GDD°C were calculated from the day after the chilling period each year to the start of the pollen season. Only temperatures above or equal to 0°C were used to calculate cumulative sums; negative temperatures were considered as 0°C (Galán et al. 2001; Jato et al. 2002; Rodríguez-Rajo et al. 2003).

Results

Defining the start of the pollen season

Start dates of the *Alnus* spp. and *Corylus* spp. pollen seasons from 1996 to 2005 defined using the 90%, 95% and 98% methods were entered into correlation analysis with monthly and 10-day mean temperature and rainfall data from October (the previous year) to February (in the year of pollination) (Tables 1 and 2). Start dates of the *Alnus* spp. and *Corylus* spp. pollen seasons calculated using the 98% method, whereby the season starts when 1% of the total catch is achieved and ends when 99% is reached, generally showed the strongest relationship with meteorological variables and, as a result, it was decided to use this method when describing characteristics of the *Alnus* spp. and *Corylus* spp. pollen seasons. It should, however, be noted that start dates defined using the 90% method had the lowest standard deviation, which is the technique often used for selecting the method for calculating the start of the pollen season (Jato et al. 2000; Laaidi 2001; Rodríguez-Rajo et al. 2003, 2004). The use of the 98% method had the advantage of including the maximum number of pollen counts in the analysis, important for taxa such as *Alnus* spp. and *Corylus* spp. that can have seasons when few pollen

Table 1 The significant correlations between start dates of *Corylus* spp. pollen seasons (1996 to 2005) and temperature and rainfall data recorded at Pershore from October (the previous year) to January (in the year of pollination)

Independent variable	*Corylus* spp. start		
	90% method	95% method	98% method
10-day mean temperature days 276 to 285 from 1 Jan	–	0.723*	0.818**
October mean monthly temperature	–	–	0.668*
10-day mean temperature days 336 to 345 from 1 Jan	–	−0.637*	–
December mean monthly temperature	–	−0.738*	−0.744*
October mean monthly rain	–	−0.642*	–

* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

grains are recorded at the trap, whilst still excluding low concentrations of pollen at the beginning and end of the season that may distort analysis (Emberlin et al. 1993; Kasprzyk et al. 2004).

Start of the pollen season

For both taxa, there is a range of 39 days in the start dates. For *Corylus* spp. pollen, the starts varied from 5 January in 1999 to 13 February in 1996. The start of the *Alnus* spp. pollen season varied from 21 January in 2000 to 29 February in 1996 (Fig. 1). The later starts dates that occurred in 1996 could be due to a cold December in 1995, a cold January and February in 1996 and a wetter than average December. There is a slight trend toward earlier *Corylus* spp. and *Alnus* spp. pollen seasons at Worcester, although this trend is removed when data from 1996 are omitted from the analysis.

Table 2 The significant correlations between start dates of *Alnus* spp. pollen seasons (1996 to 2005) and temperature and rainfall data recorded at Pershore from October (the previous year) to February (in the year of pollination)

Independent variable	*Alnus* start		
	90% method	95% method	98% method
10-day mean temperature days 276 to 285 from 1 Jan	–	–	0.680*
10-day mean temperature days 21 to 30 from 1 Jan	−0.683*	−0.770**	−0.698*
10-day mean temperature days 31 to 40 from 1 Jan	−0.845**	−0.788**	−0.708*
10-day mean rain days 306 to 315 from 1 Jan		0.644*	

* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

Annual totals and length of season

The pollen seasons of *Corylus* spp. and *Alnus* spp. at Worcester have got longer in the last few years (Fig. 2), but there is not a trend over the whole data set. The cumulative catches of *Corylus* spp. and *Alnus* spp. during the pollen seasons also changed during the study period, with seasons becoming more severe (Figs. 3 and 4). The highest annual total of *Corylus* spp. pollen was 490 grains/m^3 in 2004 and the lowest was 65 grains/m^3 in 2001. *Corylus* spp. pollen seasons follow a distinct biennial pattern of alternating high, followed by lower count years. Similarly, the highest annual sum of *Alnus* spp. pollen was also recorded in 2004 (3,467 grains/m^3) and the lowest was also recorded in 2001 (698 grains/m^3). There is a slight indication of a similar biennial pattern occurring for *Alnus* spp. although it is not so apparent and distinctive as in *Corylus* spp.; the reasons for this are not obvious in the data.

Correlation analysis

All results of correlation analysis are between start dates of *Corylus* spp. and *Alnus* spp. pollen seasons at Worcester and meteorological data recorded at Pershore unless otherwise stated. A significant positive relationship exists between start dates of the *Corylus* spp. pollen season and temperatures in October (Table 1), suggesting that lower temperatures at this time will result in earlier *Corylus* spp. pollen seasons and vice versa. Significant negative correlations feature between start dates of the *Corylus* spp. pollen season and December temperatures, which indicate that higher temperatures at this time will produce earlier starts and, conversely, low temperatures in December will cause the season to commence later. However, this depends on adequate vernalisation. This relationship is also present between *Corylus* spp. start dates (defined using the 98% method) and mean-monthly December temperatures from the CET monthly series [R=−0.804, significant at the 0.01 level (2-tailed)]. A significant negative correlation also occurs between *Corylus* spp. start dates and rainfall in October.

A significant positive relationship exists between the start of the *Alnus* spp. pollen season and temperatures in October (Table 2), these findings are comparable to the results of correlation analysis between *Corylus* spp. start dates and temperatures at this time of the year. There is also a negative relationship between start dates of *Alnus* spp. pollen seasons and temperatures during the last 10-days in

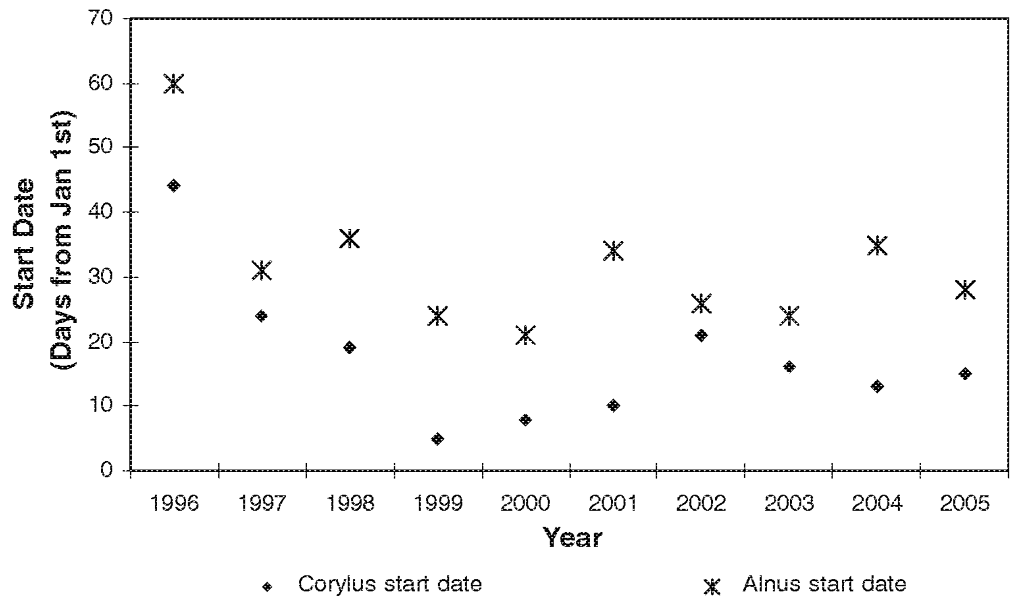

Fig. 1 Start dates of the *Alnus* spp. and *Corylus* spp. pollen seasons at Worcester (1996–2005). Pollen season start defined using the 98% method

December (R=−0.560) and mean monthly December temperatures (R=−0.567), but correlations were not significant (correlation coefficients shown between December temperatures and *Alnus* spp. start dates calculated using the 98% method). Instead, temperatures in January seem to be more important, with significant negative correlations between *Alnus* spp. start dates and temperatures from day 21 to day 40 from 1 January. A significant positive correlation also features between *Alnus* spp. start dates and rainfall at the beginning of November.

Chilling hours and growth degree days

The chilling requirements of *Corylus* spp. and *Alnus* spp. were calculated following the method of Aron (1983). Chilling hours commenced when temperatures were below the threshold of 12.5°C for two or more consecutive days and ended on 30 November each year. 30 November was chosen for the end of chilling because the results of correlation analysis showed that there is a negative relationship between temperatures in December and

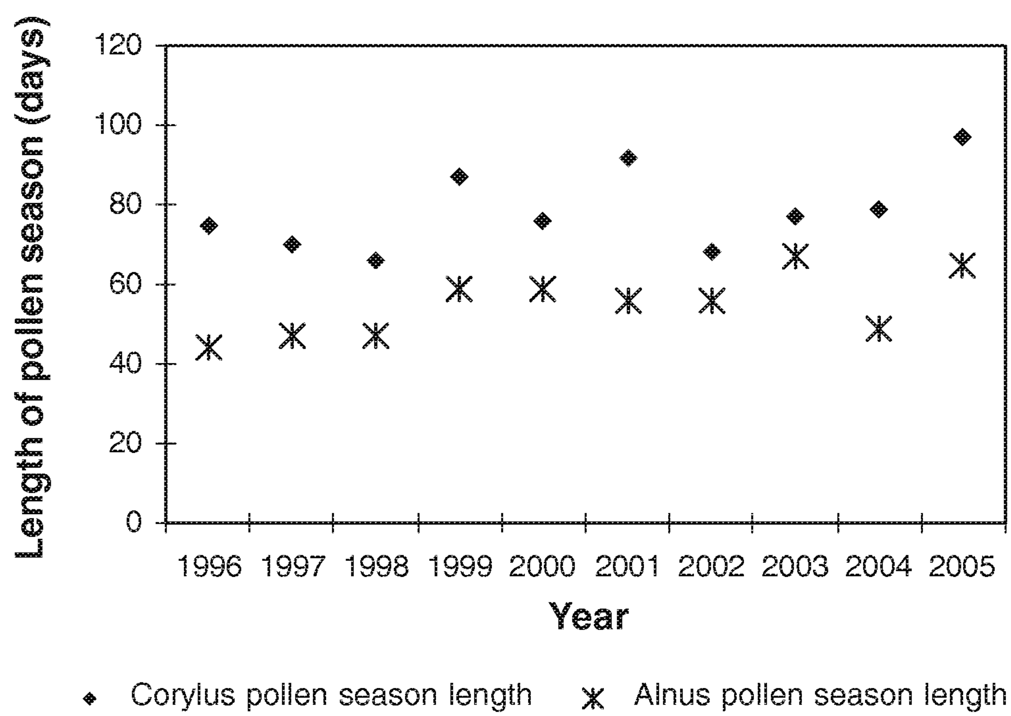

Fig. 2 Length of the *Alnus* spp. and *Corylus* spp. pollen seasons at Worcester (1996–2005). Start and end of the pollen seasons defined using the 98% method

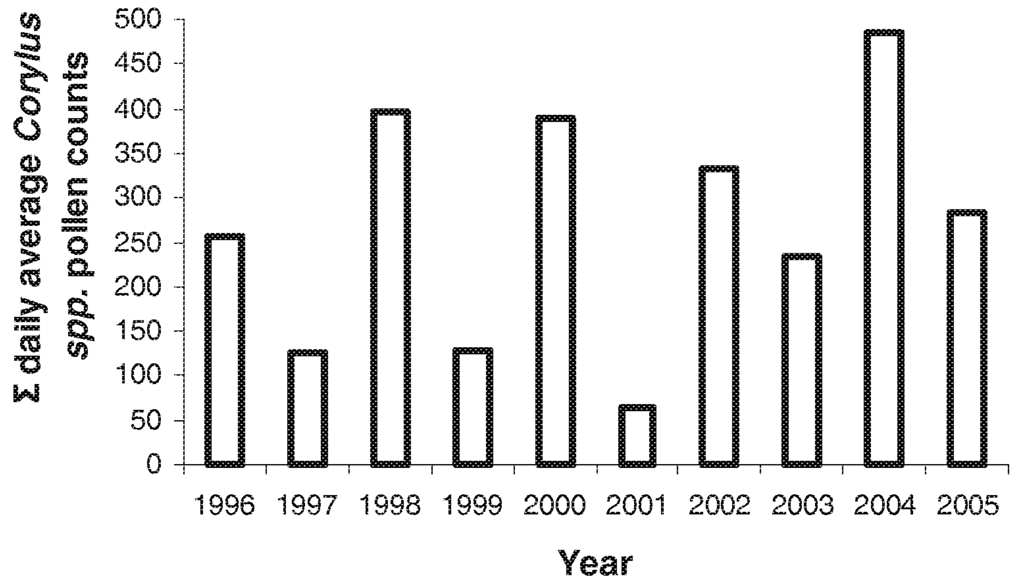

Fig. 3 Total season counts of *Corylus* spp. pollen in Worcester from 1996 to 2005. Season defined using 98% method. Daily average counts calculated as pollen grains/m^3

Corylus spp. and *Alnus* spp. start dates, which suggests that warm temperatures at this time are necessary for earlier flowering.

GDD°C were therefore calculated for both *Corylus* spp. and *Alnus* spp. from 1 December each year (Tables 3 and 4). GDD°C calculated by subtracting the base temperature of 6°C resulted in the lowest standard deviation. Correlations between hazel and alder start dates and the amount of chilling and GDD°C accumulated are generally low ($R<\pm0.2$), although a notable (but not significant) relationship exists between *Alnus* spp. start dates and chilling hours ($R = -0.384$). Conversely, there are a number of significant associations [at the 0.05 level (2-tailed)] between chilling hours and the amount of GDD°C calculated for *Corylus* spp. ($R=-0.671$) and *Alnus* spp. ($R=-0.743$), the strongest relationships being with GDD°C calculated using the threshold of 4°C (Figs. 5 and 6).

Regression analysis

Two significant correlations occurred between start dates of the pollen seasons (defined using the 95% method) and rainfall during the preceding months (Tables 1 and 2). The ability of precipitation to predict the beginning of the *Corylus* spp. and *Alnus* spp. pollen seasons was assessed by entering these rainfall variables into hierarchical multiple regression analysis with start dates of the relevant pollen seasons after temperature had been controlled for (Pallant 2001). The results of hierarchical multiple regression analysis showed that neither of the rainfall variables made

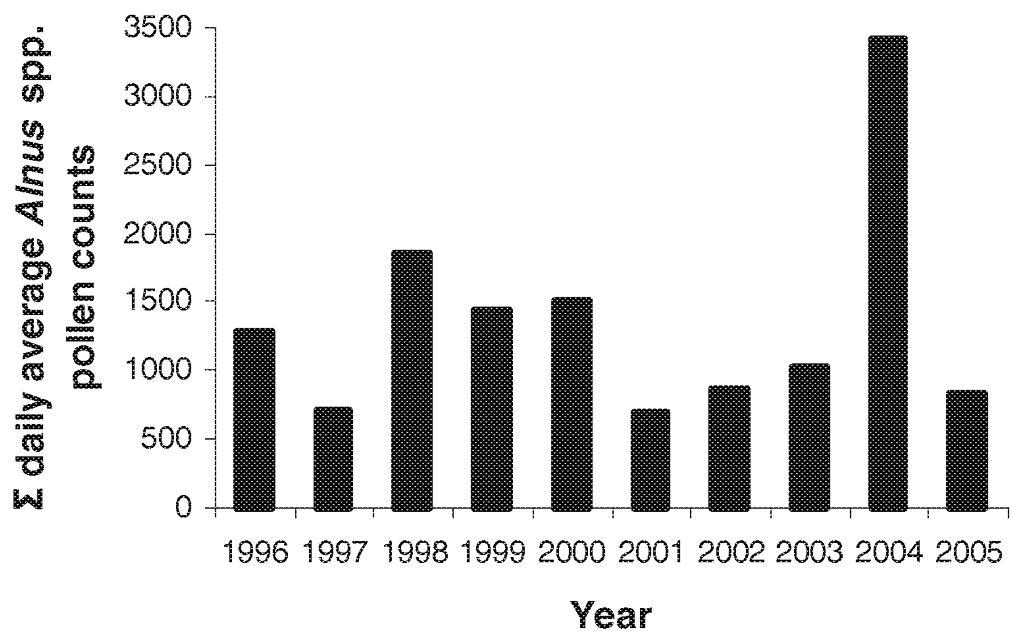

Fig. 4 Total season counts of *Alnus* spp. pollen in Worcester from 1996 to 2005. Season defined using 98% method. Daily average counts calculated as pollen grains/m^3

Table 3 Heat requirements for the start of the *Corylus* spp. pollen season calculated from December using different threshold temperatures (4–6°C)

Season	Threshold temperature (°C)				
	4	4.5	5	5.5	6
1995–1996	99.2	84.3	70.0	56.7	45.5
1996–1997	37.5	30.6	24.8	19.8	14.8
1997–1998	146.5	126.0	106.5	88.7	72.9
1998–1999	97.6	85.1	67.4	61.0	49.9
1999–2000	70.4	57.4	45.5	34.9	25.2
2000–2001	113.7	101.2	89.0	78.0	68.0
2001–2002	71.3	59.8	49.4	39.8	31.2
2002–2003	112.4	98.2	84.6	72.9	62.1
2003–2004	94.3	79.4	67.3	55.8	45.3
2004–2005	132.9	115.7	100.4	87.0	74.0
SD	31.9	28.7	25.6	22.9	20.6
Mean	97.6	83.7	70.5	59.4	48.9
CV (%)	32.7	34.3	36.4	38.5	42.1

Season start defined using 98% method; *SD* standard deviation, *CV* coefficient of variation

a unique contribution to the models ($P>0.05$), which suggests that rainfall does not significantly affect the start of the hazel or alder pollen seasons.

Following the work of Galán et al. (2005), the effects of climate change on the phenology of early flowering trees were investigated using regression analysis. Start dates of *Corylus* spp. pollen seasons had the strongest relationship with temperature data from the proceeding months (Tables 1 and 2) and, as a result, were used to construct two simple linear regression models and a standard multiple regression model with mean monthly temperatures from October and December (Table 5). Climate Change Scenario data from the United Kingdom Climate Impacts Programme (UK CIP02) are presented with a resolution of 50 km and were used to examine the affect that increases in winter temperatures would have on hazel pollen seasons. The results of this analysis (Table 6) show predicted changes to the start of the *Corylus* spp. pollen season in three periods, the 2020s, 2050s and 2080s, after daily mean temperature data produced by the UKCIP02 medium-high emissions scenario were entered into the regression models (Hulme et al. 2002). Increases in October temperatures caused the *Corylus* spp. pollen season to start later, whilst increases in December temperatures caused the *Corylus* spp. pollen season to commence earlier. A standard multiple regression model containing both October and December mean monthly temperatures resulted in little change to the start of the *Corylus* spp. pollen season.

Table 4 Heat requirements for the start of the *Alnus* spp. pollen season using different threshold temperatures (4–6°C)

Season	Threshold temperature (°C)				
	4	4.5	5	5.5	6
1995–1996	111.8	93.8	77.5	62.3	49.8
1996–1997	41.0	32.6	25.3	19.8	14.8
1997–1998	151.3	129.3	108.6	89.8	73.3
1998–1999	139.4	120.4	101.6	85.0	69.4
1999–2000	78.0	62.5	49.2	37.8	27.6
2000–2001	128.5	112.1	97.0	83.5	71.8
2001–2002	94.5	80.5	67.6	55.5	44.4
2002–2003	136.6	118.5	101.3	86.1	71.7
2003–2004	156.2	134.8	116.4	99.4	83.4
2004–2005	158.7	138.0	119.2	103.0	87.5
SD	38.4	34.5	30.9	27.5	24.2
Mean	119.6	102.2	86.3	72.2	59.4
CV (%)	32.1	33.8	35.8	38.0	40.8

Season start defined using 98% method; *SD* standard deviation, *CV* coefficient of variation

Discussion

Corylus spp. pollen seasons at Worcester show distinct biennial patterns in pollen production (Fig. 3). Such cyclic patterns of alternating high followed by low pollen production years have been seen in a number of tree species including *Betula* spp. (Emberlin et al. 1993; Emberlin 1997, 2000; Latalowa et al. 2002). These rhythmic patterns are sometimes interrupted by asynchronous years (Spieksma et al. 1995; Emberlin et al. 1997), which may explain why there was not such a distinctive pattern for *Alnus* spp. (Fig. 5).

The 2000–2001 season had the lowest annual sums for both hazel and alder pollen. There are a number of factors that may account for variations in the severity in the pollen seasons of early flowering trees, including rainfall and temperatures in the previous year and the presence of natural rhythms in pollen production. It should also be remembered that conditions at the time of the release and dispersal of pollen from the plant are also important; January 2001 had below average temperatures and above average rainfall (1975–2005 mean) and, furthermore, 2001 had the fourth wettest February and fifth wettest March in the 1975–2005 dataset.

There are a number of similarities in the temporal variations of *Corylus* spp. and *Alnus* spp. pollen seasons, which suggests that many of the environmental factors affecting one genus also affect the other. The results presented in this paper concur with other studies that have shown that the phenology of early flowering trees such as hazel and alder are greatly dependent on temperature (Frenguelli et al. 1991–1993; Frei 1998; Jato et al. 2000). For example, both *Corylus* spp. and *Alnus* spp. show a

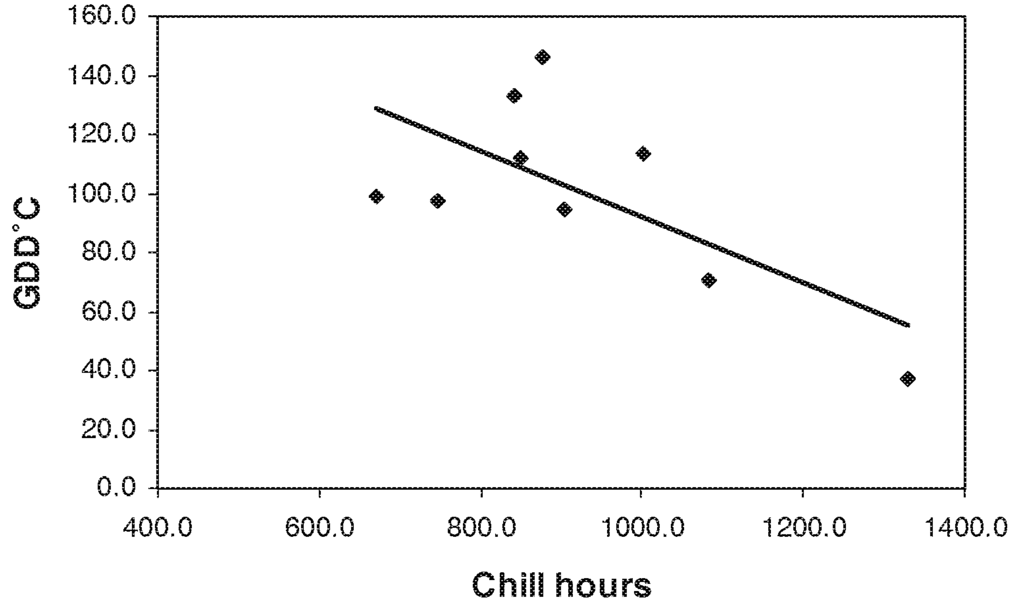

Fig. 5 The relationship between the heat requirements (GDD°C) for the start of *Corylus* spp. pollen seasons and chilling hours. GDD°C calculated using the threshold of 4°C

negative relationship with temperatures in December. These results are similar to those presented by Frenguelli et al. (1992, 1993) who demonstrated that in *Corylus* spp. there is a strong correlation between the mean temperature during the last 10 days in December and the start of the pollen season.

This relationship is illustrated by the late start dates of the hazel and alder pollen seasons in 1996 that followed a particularly cold December in 1995; December 1995 was the coldest December in the 1995–2004 dataset and the fourth coldest December since 1975. Furthermore, temperatures in January and February 1996 were also below the 1975–2005 mean, which would have compounded the affect that low temperatures during December 1995 had on the 1996 *Corylus* spp. and *Alnus* spp. pollen seasons. Start dates of *Alnus* spp. pollen seasons seem to be related to December temperatures, but the results of correlation analysis were not significant ($P<0.10$, >0.05). Instead, temperatures at the end of January and beginning of February appear to be more important. It should, however, be noted that this may have as much to do with the weather conditions during pollen release as with heat accumulation prior to flowering.

Chilling hours were calculated from the day when mean daily temperatures were <12.5°C for two or more consecutive days. Mean daily temperatures recorded at Pershore usually went below 12.5°C on day 275 from 1 January (1975–2005 mean). Coincidentally, this is the same time when significant positive correlations were found between

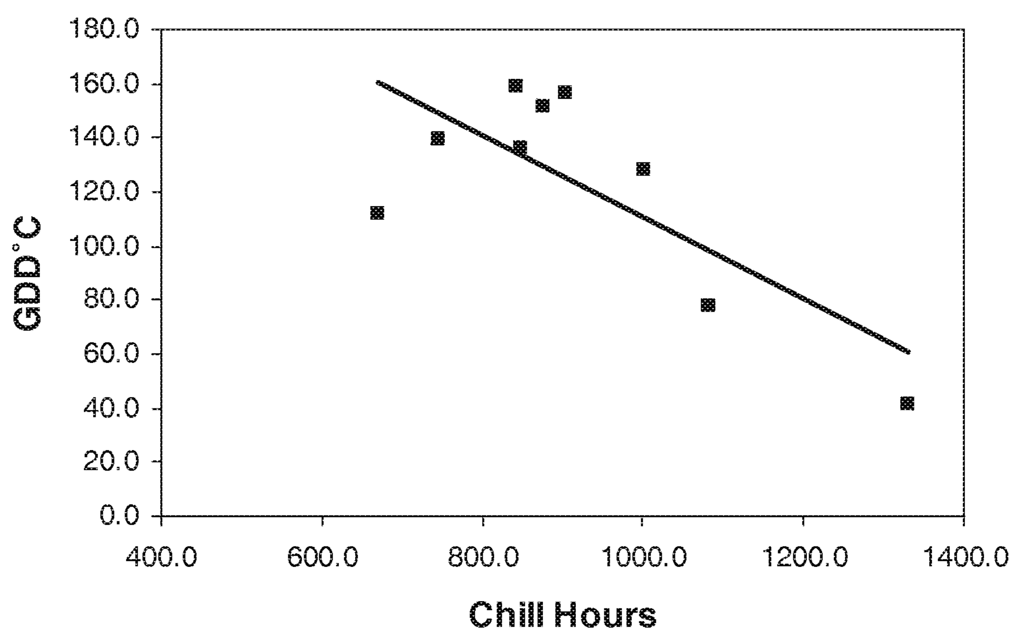

Fig. 6 The relationship between the heat requirements (GDD°C) for the start of *Alnus* spp. pollen seasons and chilling hours. GDD°C calculated using the threshold of 4°C

Table 5 Results of standard multiple regression analysis between start dates of the *Corylus* spp. pollen season and October and December mean monthly temperatures from the previous year

Regression model	Regression equation	Adjusted R^2
1	(5.372 × mean October temperatures*) − 44.063	0.378
2	45.628 − (5.824 × mean December temperatures*)	0.497
3	3.492 + (3.003 × mean October temperatures) − (4.225 × mean December temperatures)	0.551

*Variable significant at the 95% level when included in the regression model

temperatures and start dates of the *Corylus* spp. and *Alnus* spp. pollen seasons.

In Worcester, the amount of chilling hours accumulated does not have a considerable effect on the phenology of hazel and alder, probably because vernalisation is usually satisfied. It was found that start dates of both *Corylus* spp. and *Alnus* spp. pollen seasons had a significant positive relationship with temperatures in the beginning of October, but there were no significant correlations between start dates and the amount of chilling hours accumulated. This is illustrated by the fact that there were no chilling hours accumulated during the 2001–2002 season by the method used, although alternative approaches could have shown different results. Examination of temperature data from Pershore shows that October 2001 was the warmest October in the 1975–2005 dataset. Furthermore, according to the CET monthly series, October 2001 was the warmest October since instrumental records began.

Table 6 Start dates of *Corylus* spp. pollen seasons produced when UKCIP02 Climate Change Scenario data were entered into the regression models presented in Table 5

Regression model	Independent variable(s)	Estimated start date of *Corylus spp.* pollen season		
		2020s	2050s	2080s
1	Mean monthly October temperatures	24	30	39
2	Mean monthly December temperatures	13	8	1
3	Mean monthly October and December temperatures	17	17	17

Note that on average (1996–2005 mean) the *Corylus* spp. pollen season started on day 18 from 1 January

It was found that the amount of chilling hours accumulated in the autumn was related to the amount of heat required for flowering. Frenguelli and Bricchi (1998) also found that more chilling hours accumulated by the plant meant that less heat accumulation was needed for pollination. The authors noticed that when winters were relatively warm more heat was required for the plant to pollinate and vice versa.

Chilling hours were calculated using the method described by Aron (1983), a method that has been used successfully in a number of other studies on early flowering trees (Frenguelli and Bricchi 1998; Jato et al. 2000; Rodríguez-Rajo et al. 2003, 2004). The author urged caution when applying the equation to data from different sites because the model was derived using data from California only. In this study, the use of this model with threshold temperatures lower than 12.5°C or with a end of chilling date later than 30th November often resulted in the amount of chilling hours exceeding the total amount of hours in the designated period. However, the close relationship witnessed between the chilling hours calculated using this method and GDD°C accrued by both *Corylus* spp. and *Alnus* spp. (Figs. 5 and 6) suggests that this method gives a reasonable representation of the amount of chilling accumulated in the autumn at Worcester.

Previous work has shown that 4.5°C is a threshold above which temperatures are considered to be effective for growth (Faust 1989; Frenguelli et al. 1993). In studies of this kind, authors often determine which threshold to use for calculating GDD°C by examining the standard deviation (SD) and coefficient of variation (CV) (Frenguelli and Bricchi 1998; Jato et al. 2000, 2002; Galán et al. 2001; Rodríguez-Rajo et al. 2004). In this study, GDD°C calculated using the threshold of 6°C gave the lowest SD and the highest CV for both *Corylus* spp. (Table 3) and *Alnus* spp. (Table 4). However, GDD°C calculated using lower thresholds (4 and 4.5°C) have a stronger relationship with chilling hours and as a result might be more representative of the heat requirement of the early flowering trees examined. The amount of GDD°C accumulated above 4.5°C at Worcester averaged 84 h for *Corylus* spp. and 102 h for *Alnus* spp.

The entry of temperature data produced by the UKCIP02 medium-high emissions scenario into regression models constructed using *Corylus* spp. start dates and mean monthly October and December temperatures (Table 5) helped to illustrate the relationship between start dates and winter temperatures. The UKCIP02 Climate Change Scenarios are based on data from 1961–1990 (Hulme et al. 2002). Consequently, there is a degree of error in this analysis because predicted temperature increases for the 2020s, 2050s and 2080s were added to the 1995–2004 mean of October and December temperatures recorded at Pershore. These models were not designed for long-term forecasting, but are used to

show the theoretical impact of expected climate change on the start of *Corylus* spp. pollen seasons.

Conclusion

The results indicate that *Alnus* spp. and *Corylus* spp. pollen seasons have changed in the Worcester area over the last 10 years, with seasons becoming longer and more severe in recent years, but long term trends cannot be discerned with this relatively short data set. Although the analyses are based on Worcester the results have a wider application and have implications for other regions.

The Central England Temperature series shows that there has been warming of the UK climate since the seventeenth century. This warming has been greater in winter (1.1°C) than in summer (0.2°C) (Hulme and Jenkins 1998). The results of this study concur with previous work that has found temperature to be the main factor affecting the phenology of early flowering trees, with *Corylus* spp. pollen seasons appearing to be particularly responsive to temperature. In the UK, there are sufficiently long periods in the 3–9°C range, which means that autumn and winter chilling is probably not as important as heat accumulation (Faust 1989), although the entry of warmer October temperatures into a simple linear regression model showed that start dates of *Corylus* spp. pollen seasons could get later in a warmer climate. However, it is possible that warmer temperatures during the heat accumulation period may offset any increases in temperatures during vernalisation.

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